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EVALUATION OF THE MECHANICAL PROPERTIES OF YARNS FOR BALLISTIC APPLICATIONS

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13. ABSTRACT

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TECHNICAL REPORT
73-60-CE

EVALUATION OF THE MECHANICAL PROPERTIES OF YARNS FOR BALLISTIC APPLICATIONS

by

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J. G. Donovan
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Dedham, Massachusetts

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Clothing and Personal Life Support Equipment Laboratory
U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts 01760

FOREWORD

This report is based on the unclassified portions of the final report on Contract No. DAAG 17-70-C-0086 entitled "A Study of Felts for Body Armor" February, 1972, by the same authors. It covers work performed during the period of December 1969 to December 1971. Contractual matters at Fabric Research Laboratores were handled by Dr. M. M. Platt; the project officer at Natick Laboratories was Mr. Louis I. Weiner. Author W. D. Claus, Jr., is now affiliated with the Natick Laboratories and author W. D. Freeston, Jr., with the Georgia Institute of Technology. The authors wish to thank Ms. Dorothy Wignall for typing the manuscript for publication.

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ABSTRACT

Methods are described which were used to screen many commercially available yarns for ballistic applications. The techniques which were used include low and high strain rate tensile tests, determination of longitudinal strain wave speed of propagation as a function of strain level, and measurement of transverse critical velocity, the only ballistic test which was used. In the tensile tests, the yarn modulus and strength generally increased and the elongation decreased as the strain rate increased. The strain wave speed of propagation was found to increase nearly three-fold in some nylons with increasing strain level, while the speed remained nearly constant in polypropylene.

1. INTRODUCTION

a. Program Objectives and Scope

The overall goal of this study was to identify in needle-punched felt armor systems the important factors which lead to high levels of ballistic performance. This goal is important because any possible improvements of ballistic performance in personnel armor translate into a lighter piece of equipment for the soldier, or conversely increased protection at the same weight. Fiber characteristics, patterns of fiber orientation, and multi-material panels were investigated. Only commercially available fibers were used on this program. Ballistic information pertinent to woven armor systems was also reported. Using the results developed on the program, prototype felts were designed, manufactured on commercial equipment, ballistically evaluated, and delivered to NLABS. That ballistic information is classified "Confidential." The selection of textile materials for ballistic applications involves trade-offs of fiber properties: the determination of those properties is the subject of this report.

b. Ballistic Impact of Nonwoven Textile Structures

Interest in nonwovens for personal armor arose for a very simple reason: it was found that needle-punched felts were ballistically superior to traditional woven fabrics at light areal densities (72 oz/sq yd). Therefore, for body armor, a potential weight saving existed, a prime consideration in gaining acceptance by the foot-soldier.

Generally speaking, the impact mechanics of felt is poorly understood at this time, as emphasized by Laible and Henry.[1] Because of the additional complications posed by an analysis of needle-punched felts, it was decided to investigate the properties of fibers, yarns, fabrics, and simulated structures initially.

Past work[2] has shown that for conventional polymeric materials the higher the fiber tenacity, the better its performance in ballistic applications. This is undoubtedly because the higher tenacity fibers usually exhibit: 1) greater areas under their stress-strain diagrams (i.e., greater energy absorption) at high rates of straining; 2) higher transverse critical velocities; 3) higher moduli and therefore higher velocities of propagation of strain down the fiber axis away from the point of impact. The latter enables a greater length of the fiber to participate in the absorption due to a long post-yield flow region. However, at high rates of straining the time scale of the event is too short for viscous deformation to take place; the material breaks at an extension and load only somewhat greater than that of the yield and lower than that achieved in a similar high tenacity fiber.

It should also be noted that although glass, metal and the new refractory fibers (e.g., Boron, graphite) have high moduli and therefore high velocities of longitudinal strain propagation and a high rupture stress, they exhibit poor energy absorption and very low critical velocities. This is due to their low characteristic rupture strains.

The foregoing illustrates that for maximum ballistic performance a fiber with the highest modulus, tenacity and rupture strain is probably required. However, a high value of two of these properties and a low value of the third can result in poor ballistic performance. The optimum material will probably have the maximum combination of high strain propagation velocity and large energy absorption at high rates of straining.

The general, guiding principle regarding fabric structure is: get as much material participating in the energy absorbing process as possible for maximum ballistic performance. Several energy absorbing mechanisms are operative, the more important of which are yarn straining and strain wave propagation away from the impact point.

A literature survey[3-6] of ballistic needle-punched felts revealed that most past effort was spent on optimizing manufacturing processing variables. FRL®'s approach to improving nonwoven armor was essentially a model studies technique. Enough work appeared to have been done on felt processing studies to indicate that further large improvements in ballistic performance were not to be achieved in that direction. A study of how basic fiber and structure variables affect energy absorption and ballistic performance seemed promising. Therefore, the program began by screening many commercially available yarns for later use in model structures.

In order to identify materials which would possess the desired characteristics as outlined above, four distinctly different types of tests were used — low and high strain rate tensile tests, a strain wave speed as a function of strain level test, and a transverse critical velocity test, the only ballistic yarn screening test used.

2. LOW STRAIN RATE YARN TENSILE TESTS

The mechanical properites of twenty-seven yarns were measured using an Instron tensile tester and are reported in Table I. All tests were carried out using a 5 inch gauge length and a 100 %/min strain rate. The reported denier, tenacity, rupture elongation and moduli are averages of at

TABLE I

LOW STRAIN RATE YARN TENSILE PROPERTIES

Yarn	Nom Den per Fil	Yarn Denier	Breaking Tenacity (gpd) Avg	Breaking Tenacity (gpd) CV	Rupture Elongation (%) Avg	Rupture Elongation (%) CV	Initial Modulus (gpd) Avg	Initial Modulus (gpd) CV	Second Modulus (gpd) Avg	Second Modulus (gpd) CV	Energy ($\frac{gm}{den}\frac{in}{in}$x100)
Nylon, Du Pont											
330 High Tenacity											
420-68-1Z	6.2	416	7.76	1.0	16.8	5.5	37.3	2.8	91.2	1.4	74.9
100-34-Z	3.0	101	6.56	1.8	27.2	8.7	37.5	4.0	67.6	2.5	----[a]
70-34-1/2Z	2.1	70	6.94	0.9	18.8	10.4	47.2	3.7	74.5	2.2	83.[illegible]
728 High Strength											
840-140-R20	6.0	954	9.25	1.4	19.4	2.3	32.8	6.2	83.8	2.1	83.4
702 Bright Ind											
840-140-1/2Z	6.0	845	8.44	1.2	19.2	4.3	40.4	[illegible].0	86.2	1.7	89.7
288 High Elong											
140-14-1/2Z	10.0	142	5.15	1.7	31.4	9.6	37.8	5.2	47.1	2.9	----[a]
140-68-Z	2.1	142	5.41	2.4	27.5	10.4	34.2	3.7	51.3	2.8	----[a]
714 Bright Ind											
840-140-R20	6.0	844	8.82	1.7	19.2	5.5	38.3	4.2	86.6	1.7	88.2
Nylon, Allied											
1A03 High Modulus											
100-32-1/2Z	3.1	99	5.83	3.3	25.3	9.8	26.5	2.8	58.3	3.0	----[a]
1Q70 High Tenacity											
840-136-1/2Z	6.2	855	8.87	1.9	20.2	5.3	35.4	2.9	92.1	4.0	91.8
Nylon, Monsanto											
A07 High Tenacity											
840-140-1/3Z	6.0	849	10.0	2.4	16.2	3.1	50.0	2.5	112.0	3.7	72.2
A05 High Tenacity Fatigue-Resistant											
840-140-Z	6.0	868	8.74	1.1	18.5	3.3	44.2	3.0	95.2	1.9	77.1

[a]Not measured.

TABLE I (Cont.)

LOW STRAIN RATE YARN TENSILE PROPERTIES

Yarn	Nom Den per Fil	Yarn Denier	Breaking Tenacity (gpd)		Rupture Elongation (%)		Initial Modulus (gpd)		Second Modulus (gpd)		Energy ($\frac{gm}{den}\frac{in}{in}$ x100)
			Avg	CV	Avg	CV	Avg	CV	Avg	CV	
Nylon, Monsanto											
A06 High Strength Improved Durability 840-140-Z	6.0	859	8.57	1.2	19.5	5.6	43.1	1.7	92.6	3.1	82.0
E02 High Tenacity 840-68-1/2Z	12.0	834	8.17	0.7	17.0	3.1	45.7	2.4	87.3	2.2	70.6
Nylon, Fiber Ind											
B60 High Tenacity 840-140-1/2Z	6.0	888	8.34	1.1	15.9	3.6	45.4	2.9	91.8	2.1	----[a]
Nomex, Du Pont											
430 Regular 200-100-0	2.0	198	5.27	1.3	22.0	6.4	121.0	9.2	---[b]		89.4
Polyester, Fiber Ind											
770 High Tenacity 440-96-1/4Z	4.6	456	7.80	0.8	12.0	2.3	111.0	3.6	---[b]		51.3
785 High Tenacity 840-74-1/4Z	11.4	858	8.15	1.4	11.8	3.4	112.0	2.4	---[b]		----[a]
Polyester, Enka											
Experimental 250-48-0/4Z	5.2	275	5.74	2.4	10.6	16.4	134.0	2.7	---[b]		----[a]
Fortisan, Celanese											
36 High Tenacity 800-800	1.0	826	8.31	2.8	6.9	3.3	196.0	5.5	---[b]		30.0

[a]Not measured.

[b]Does not apply.

TABLE I (Cont.)

LOW STRAIN RATE YARN TENSILE PROPERTIES

Yarn	Nom Den per Fil	Yarn Denier	Breaking Tenacity (gpd) Avg	Breaking Tenacity (gpd) CV	Rupture Elongation (%) Avg	Rupture Elongation (%) CV	Initial Modulus (gpd) Avg	Initial Modulus (gpd) CV	Second Modulus (gpd) Avg	Second Modulus (gpd) CV	Energy $\left(\frac{gm}{den}\frac{in}{in}x100\right)$
Polypropylene, Enjay 201 Medium Tenacity 840-140-1/2Z	6.0	852	5.97	4.3	28.5	8.1	50.7	5.5	----[b]		119.1
Polypropylene, ICI U100 High Tenacity 1140-228	5.0	1143	7.55	1.3	19.1	4.8	90.5	1.9	----[b]		91.6
Polypropylene, Hercules 301 Medium Tenacity 840-140-0	6.0	867	6.13[c]	1.2	33.0	16.6	54.7	3.8	----[b]		144.0
Polypropylene, SRI Experimental[d] 48-6-4	8.0	33-51	7.50	9.7	14.0	14.4	73.5	17.6	----[b]		----[a]
Polypropylene, NLABS Experimental[d] VEE-1604/S	---	916	6.89	2.5	34.2	4.0	33.1	2.3	----[b]		149.9
VEE-2589	---	861	6.22[e]	1.6	33.0	5.0	47.7	4.1	----[b]		141.9
Celcon, Celanese (spun by FRL®) Experimental 700-34	20.6	891	3.41	3.3	31.8	13.1	32.0	4.6	----[b]		----[a]

[a] Not measured.

[b] Does not apply.

[c] Maximum tenacity was 6.24 gpd at 29.3% elongation.

[d] Warp yarns taken from fabric.

[e] Maximum tenacity was 6.33 gpd at 29.0% elongation.

least ten tests per sample. The two moduli reported for nylon in Table I require explanation. For this purpose, a typical tenacity-elongation curve is sketched in Figure 1. There are two distinct linear regions of the curve - AB and BC. The calculated moduli based on these two regions are reported in Table I as initial modulus and second modulus respectively.

The last column in Table I is the quasi-static energy-to-rupture. To determine these energies, typical tenacity-elongation curves were plotted (Figures 2-7) and the areas under the curves were measured with a planimeter. The end point of each curve in Figures 2-7 is an average of experimentally measured rupture points for each yarn.

The coefficient of variation is the standard deviation expressed as a percentage of the arithmetic mean and gives a measure of the spread in the data in terms of the mean. As shown in Table I, the coefficients of variation are low, indicating little scatter in the experimental data. The few exceptions are explainable. The high coefficients of variation for the SRI polypropylene are expected for an experimental fiber; the Celcon sample has evidently degraded during the several years since it was spun, according to FRL® laboratory notebooks; and finally, the Enka polyester varies only in elongation.

With the Instron testing completed, the samples to be piston tested ($\dot{\epsilon}$ = 7200 %/sec) were selected. Yarns with high tenacity, high elongation, and high modulus were sought. Thus, Celcon was immediately rejected, the Nomex and Fortisan as single representatives were kept. Of the three polyesters, the 785 was dropped because of its 11.4 denier per filament. Of the remaining two materials, the 770 was kept on the basis of its high tenacity, high elongation and respectable modulus.

Figure 6 aids in the polypropylene selections. The ICI sample (1) was chosen because of its high tenacity, and the QM VEE-1604/S sample (2) was chosen because of its high elongation. Samples 3, 4, and 5 are quite similar; the Hercules 301 sample (4) was chosen on an energy basis (see last column of Table I) because it is commercially available.

Of the nylons, the Du Pont of and 420 denier and 70 denier were kept because the effect of denier per filament variation was of interest during a later phase of the program. The Du Pont 330 in 100 denier had nothing special to recommend it and hence was deleted. The Du Pont 288's were available for denier per filament study but were rejected in favor of the 330's on the basis of 288's low tenacity. In the Du Pont 700 series, the 702 was kept because of its high

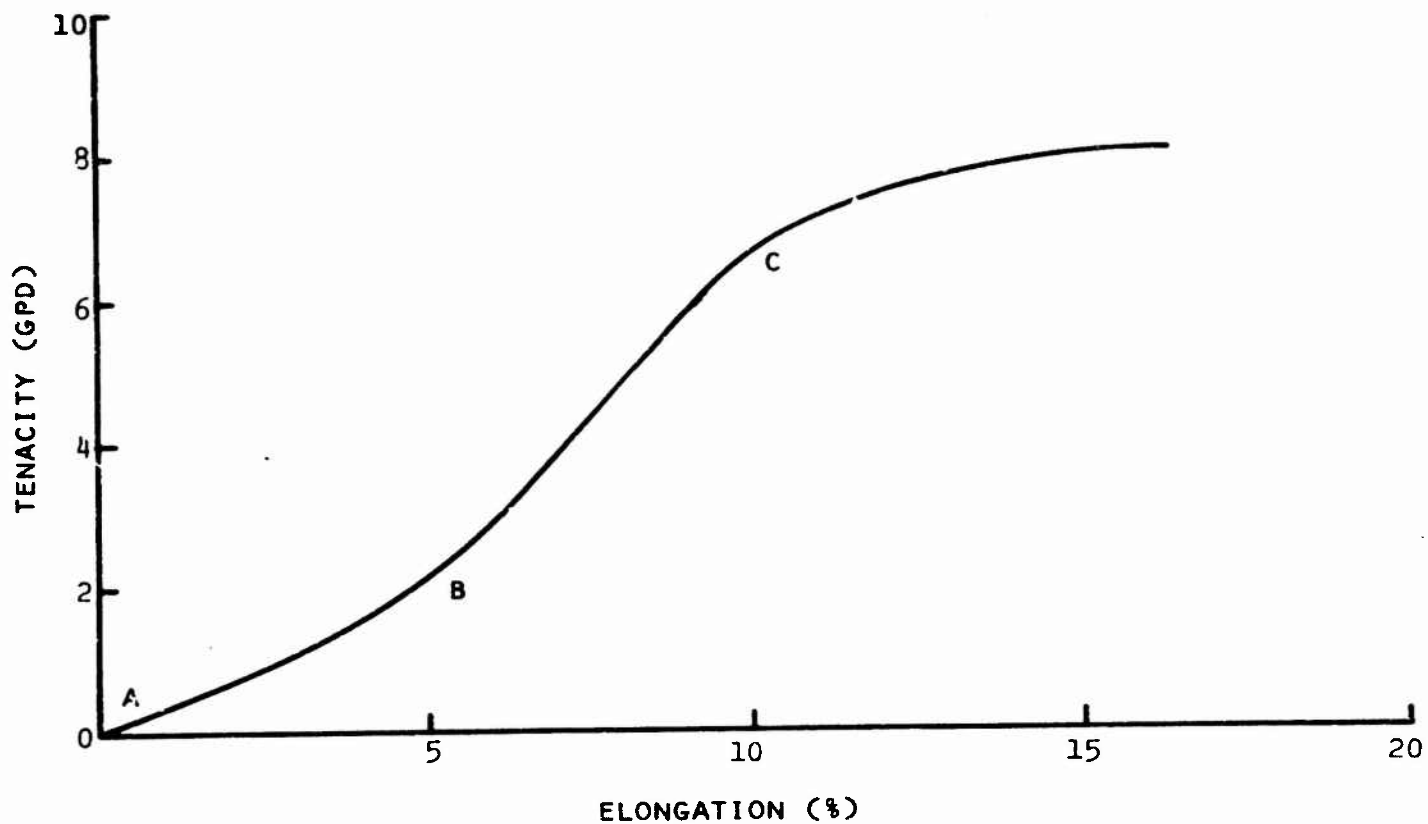


Figure 1. Typical Nylon Tenacity-Elongation Curve
($\dot{\varepsilon}$=1.6 %/sec)

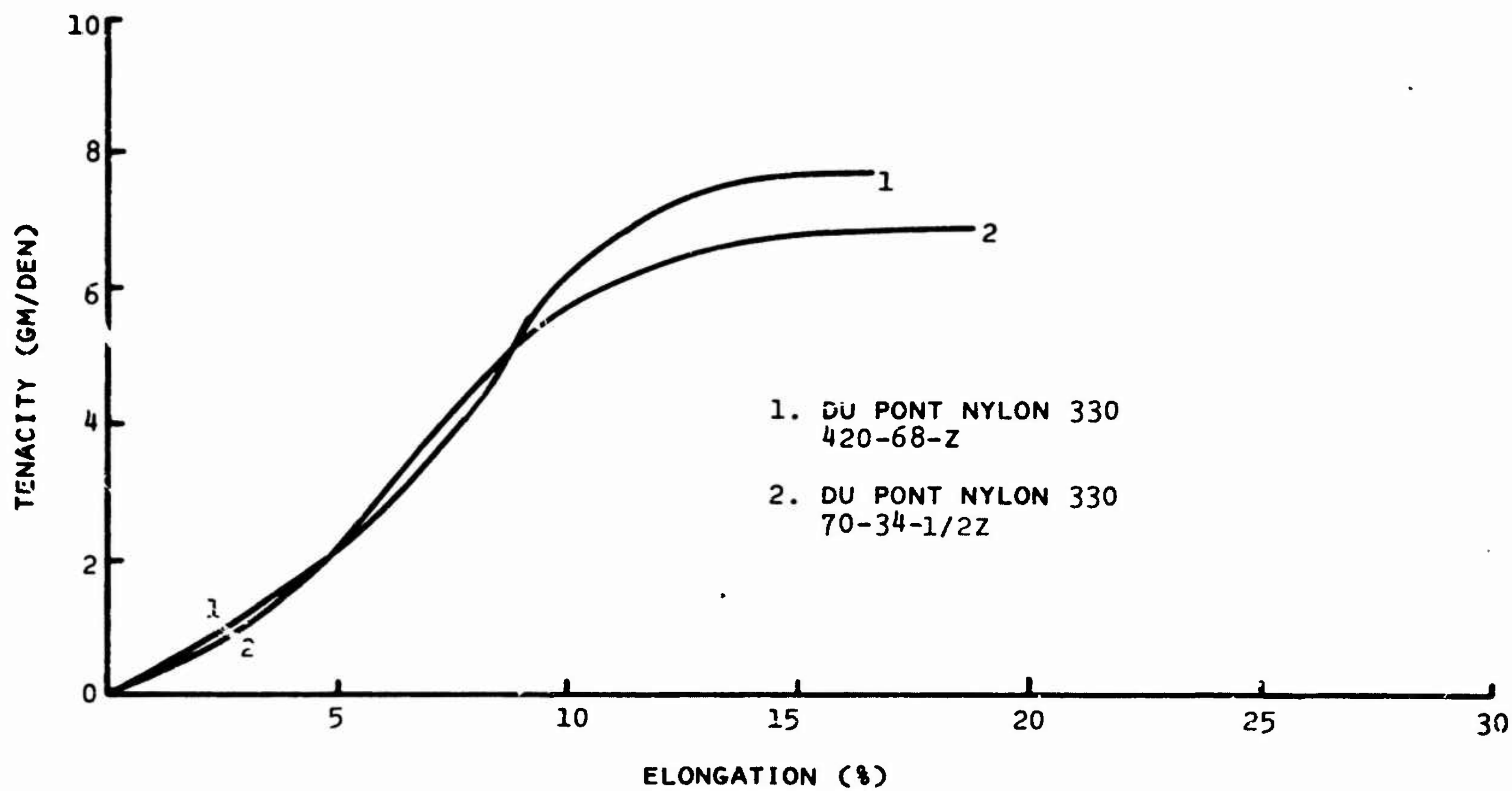


Figure 2. Typical Yarn Tenacity-Elongation Diagrams - Nylons

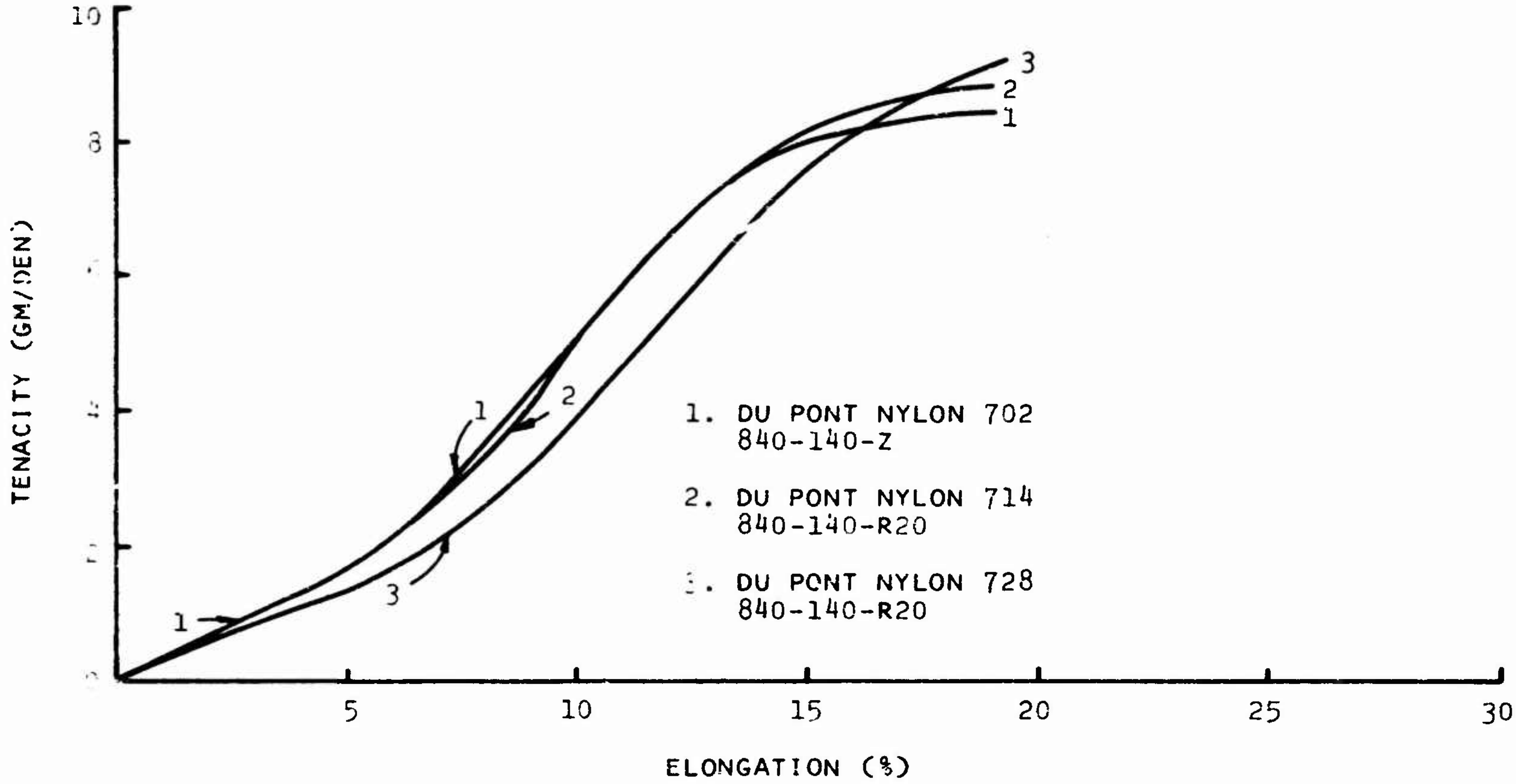


Figure 3. Typical Yarn Tenacity-Elongation Diagrams - Nylons

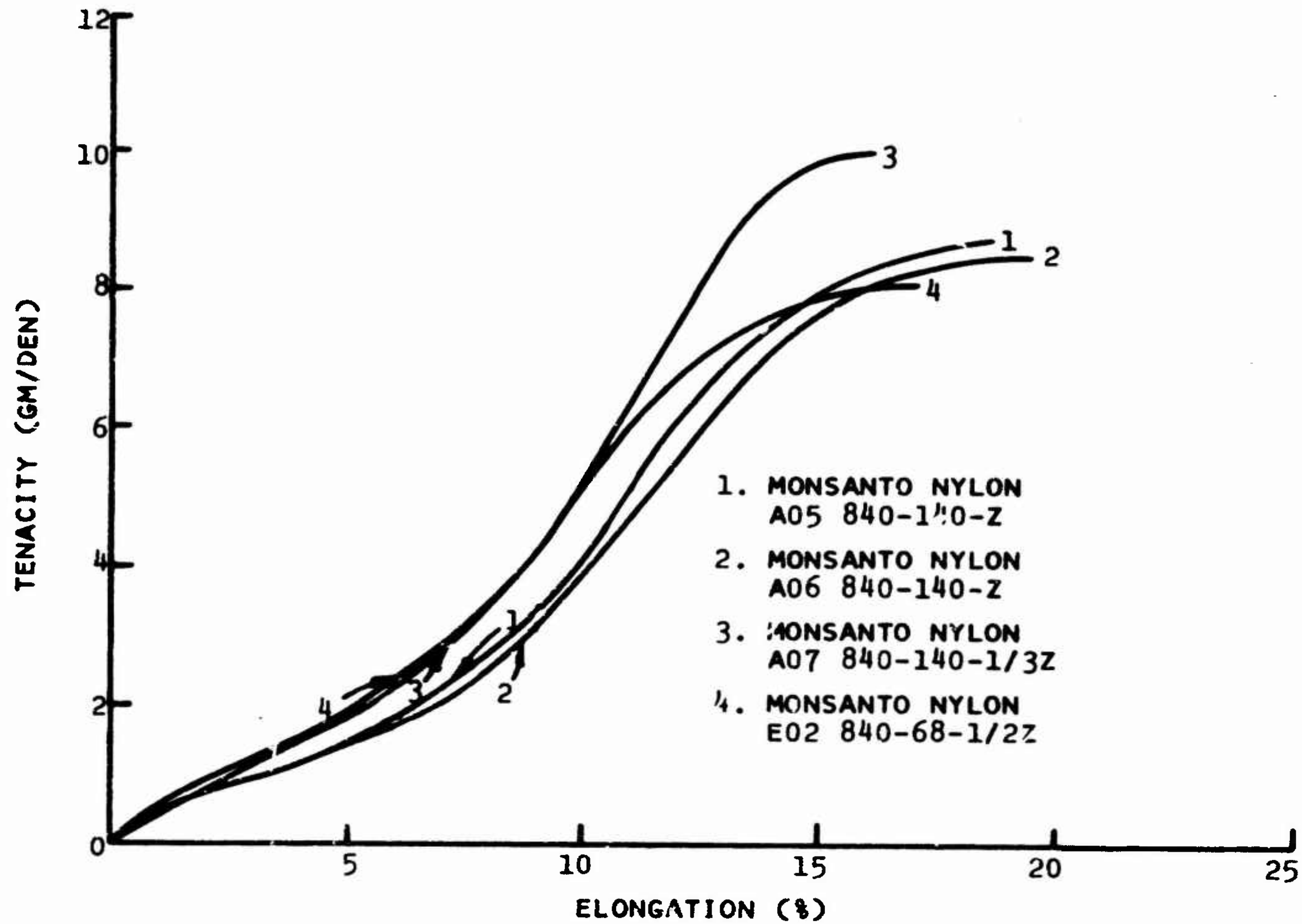


Figure 4. Typical Yarn Tenacity-Elongation Diagrams - Nylons

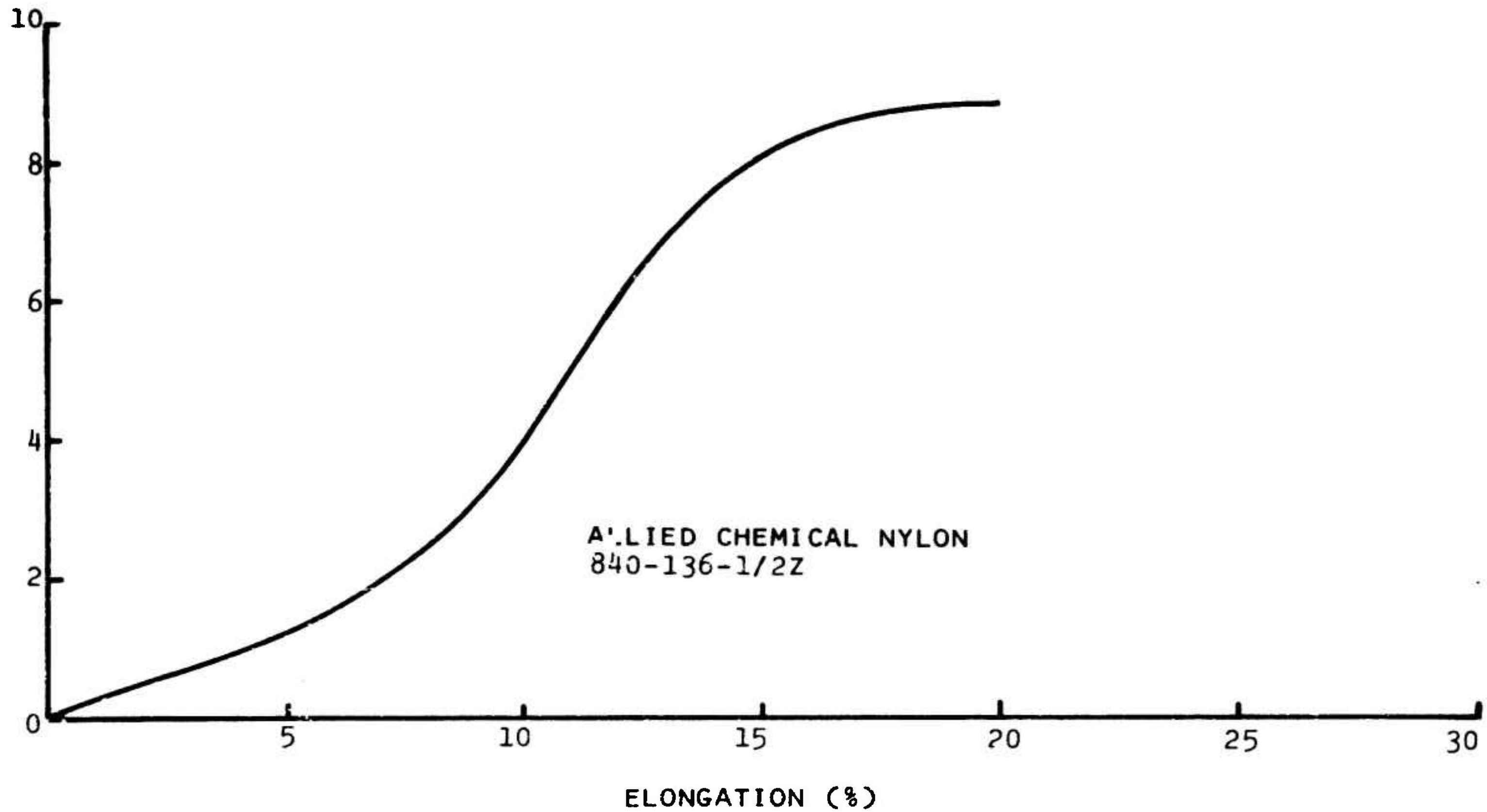


Figure 5. Typical Yarn Tenacity-Elongation Diagram - Nylon

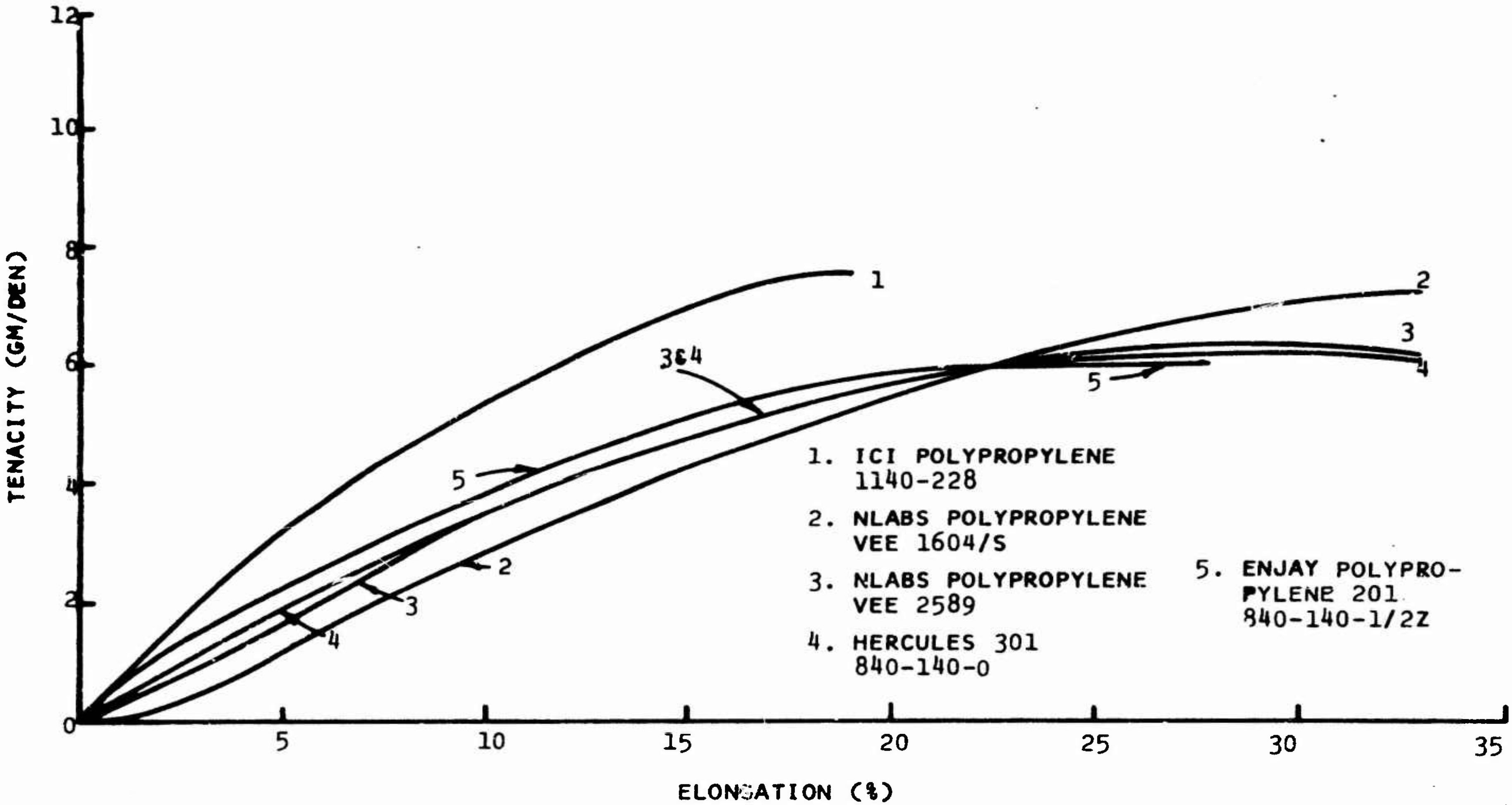


Figure 6. Typical Yarn Tenacity-Elongation Diagrams - Polypropylenes

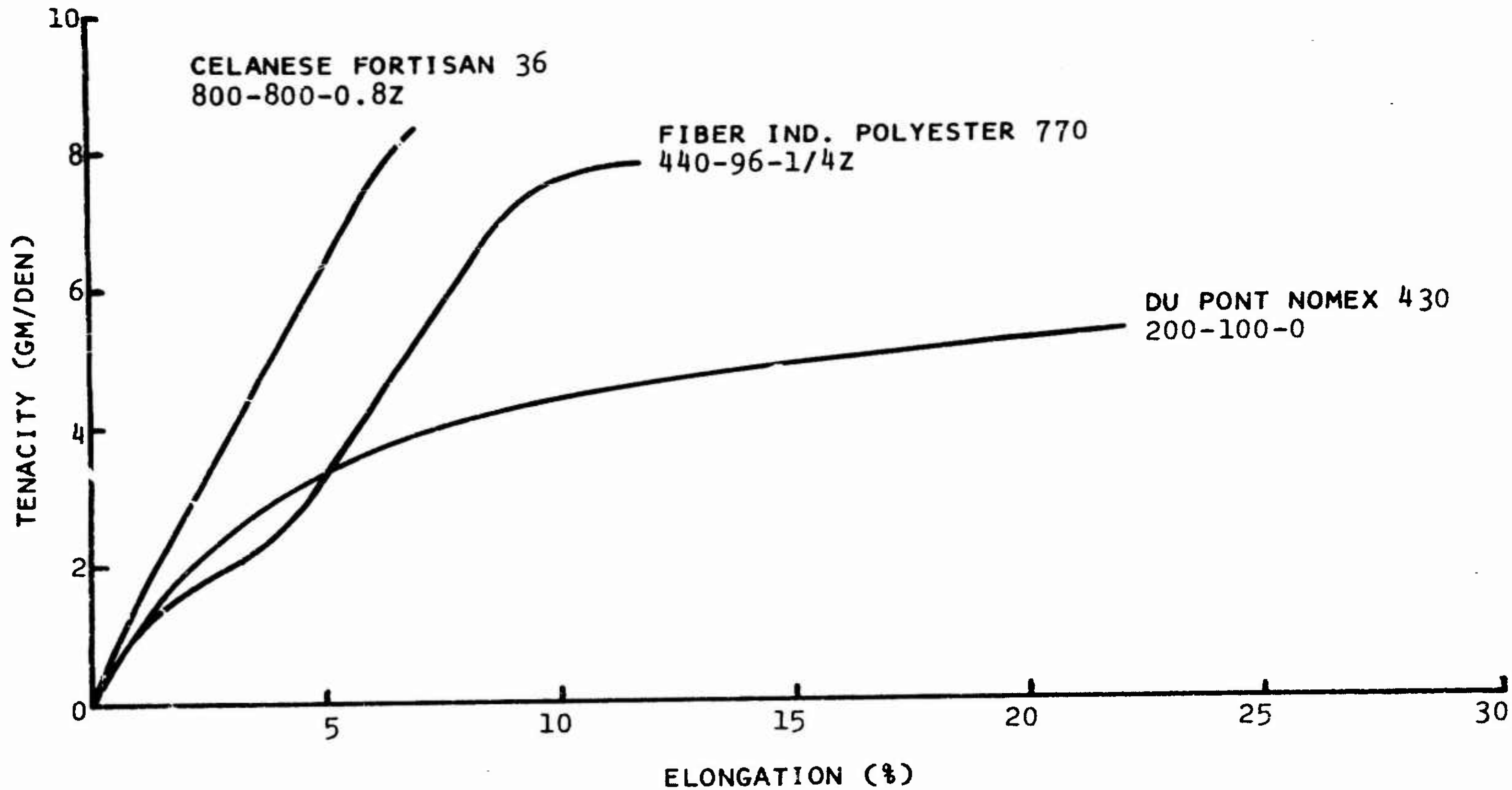


Figure 7. Typical Yarn Tenacity-Elongation Diagrams - Fortisan, Polyester, Nomex

modulus and the 728 because of its tenacity. The Fiber Industries B-60 was deleted since it appears no better than the Du Pont 700's. This left the Allied and Monsanto nylons to sort. The Allied nylons were not substantially different from the selected Du Pont yarns and were therefore dropped. Figure 4 shows the tenacity-elongation curves for the Monsanto nylons. The A07 (sample 3) was chosen because of its 10 gpd tenacity. The three other Monsanto nylons were not in any way superior to those already chosen and were dropped.

Summarizing the above discussion, the following eleven yarns were selected for piston testing ($\dot{\epsilon}$ = 7200 %/sec):

Du Pont nylon, type 330, 420-68-1Z
Du Pont nylon, type 300, 70-34-Z
Du Pont nylon, type 702, 840-140-1/2Z
Du Pont nylon, type 728, 840-140-R20
Monsanto nylon, type A07, 840-140-1/3Z

ICI polypropylene, type U100, 1140-228
Hercules polypropylene, type 301, 840-140-0
NLABS polypropylene, VEE-1604/S

Fiber Industries polyester, type 770, 440-96-1/4Z

Nomex

Fortisan 36.

3. HIGH STRAIN RATE YARN TENSILE TESTS

a. Description of Test Procedure

The FRL® high-speed piston tester was the instrument used to obtain the high strain rate tensile properties of the yarns. Tho load is applied in this instrument by a gas driven piston attached to the jaw gripping and lower end of the test specimen; the upper jaw is fixed. Jaw speeds to 100 ft/sec can be obtained.

The upper jaw is attached to the instrument frame through a piezoelectric crystal force gauge. The rapid load increase is detected by this gauge as a voltage change which is fed into a dual-beam CRT oscilloscope. The specimen extension is determined by means of magnetic tape on which a constant known frequency signal is pre-recorded. The tape is fastened to the lower jaw and pulled through a recorder head fixed to the instrument frame above the upper jaw with the signal fed into the second beam of the oscilloscope. The two signals are displayed simultaneously and photographed. Knowing the

sweep rate of the scanning beam and the recorded frequency on the tape, it is possible to determine crosshead speed and sample extension as a function of load.

b. Discussion of Results

A jaw speed of 60 ft/sec and a gauge length of 10 inches were used. (This resulted in 7200 %/sec strain rate.) From the piston tester photographs, load-elongation data were obtained. At least ten tests were performed for each yarn. Typical tenacity-elongation curves for all eleven yarns are shown in Figures 8, 9, and 10. These were obtained by choosing a typical curve from the series of photographs. The curves were cut off or, if necessary, extended to an average end point. The high strain rate tensile properties of the yarns are presented in Table II. Coefficients of variation are also included. The maximum tenacity is reported, which in some cases is greater than the breaking tenacity (see Figure 8). The reported values are averages of at least ten tests. The energy in column four is the area under the typical tenacity-elongation curve. The area was determined with a planimeter and the reported value is the average of three measurements. Table III contains the percent changes of the piston values from the Instron values.

The Fortisan test specimens did not fail within the gauge length when clamped in flat jaws. Consequently, the breaking elongation of Fortisan was determined by extrapolating a typical load-elongation curve obtained using the flat jaw system a small distance to the average load level obtained using a capstan grip system. Due to stress concentrations at the jaws, the yarn in the flat jaws prematurely fails but the load-elongation curve is believed to be accurate. The capstan system relieves the stress concentrations and an accurate breaking load is obtained. The capstan system can not be used for the entire test because the gauge length is then indeterminate. All the other yarns failed within the gauge length when tested with flat jaws.

The piston tests showed a general 20% change in mechanical properties compared with the Instron data: the modulus and breaking tenacity increased while the rupture elongation and energy decreased. As the data in Table II and the load-elongation diagrams in Figure 9 show, two of the polypropylene yarns still exhibit a large rupture elongation at high rates of straining. The curve for Nomex in Figure 10 is also interesting. A significant elongation is maintained at the high strain rate, and the modulus is much greater than the polypropylene moduli.

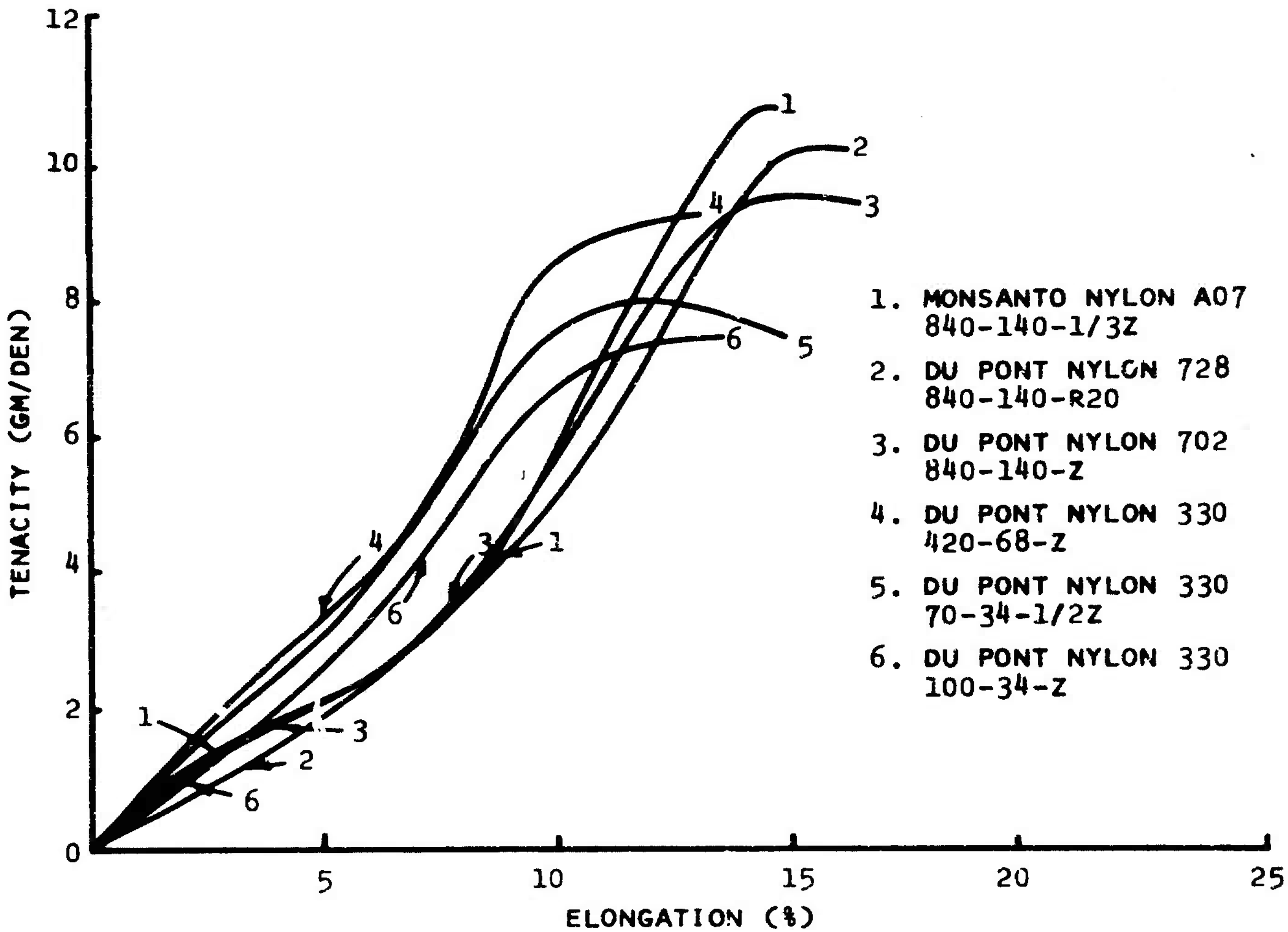


Figure 8. High Strain Rate Tenacity-Elongation Curves - Nylons ($\dot{\varepsilon}$ = 7200 %/sec)

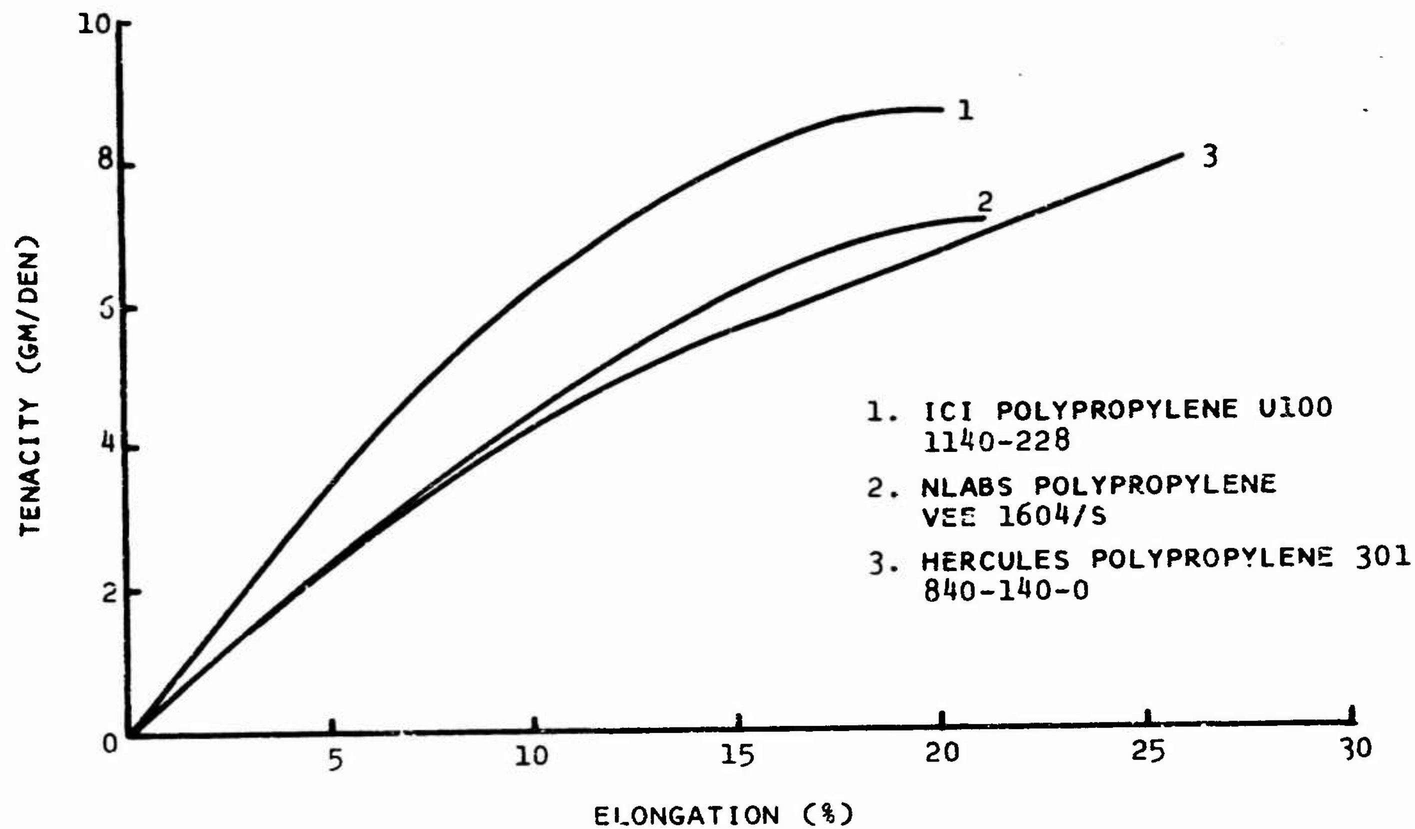


Figure 9. High Strain Rate Tenacity-Elongation Curves - Polypropylene
($\dot{\varepsilon}$ = 7200 %/sec)

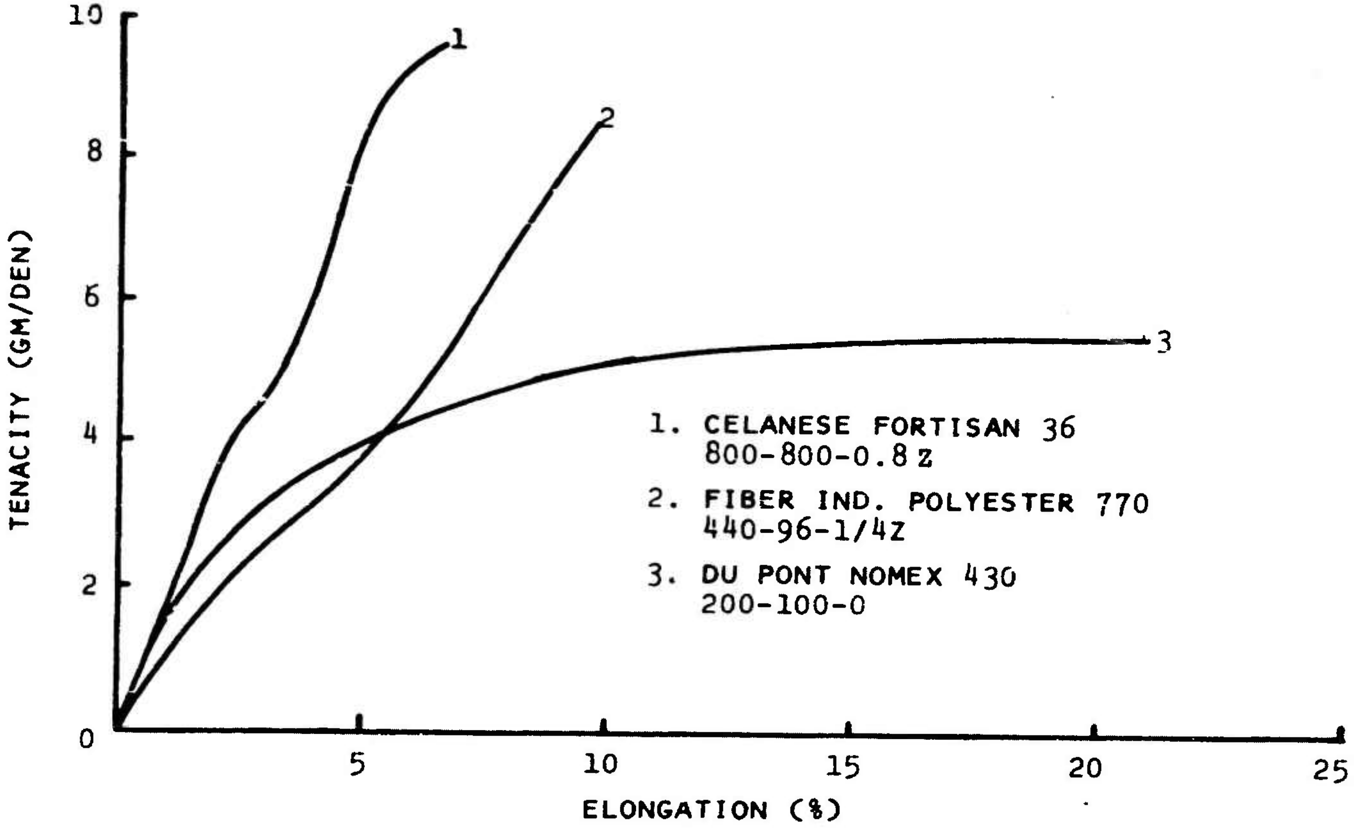


Figure 10. High Strain Rate Tenacity-Elongation Curves - Fortisan, Polyester and Nomex ($\dot{\varepsilon}$ = 7200 %/sec)

TABLE II

HIGH STRAIN RATE YARN TENSILE PROPERTIES

Yarn		Modulus (gpd)	Maximum Tenacity (gpd)	Rupture Elongation (%)	Energy $\left(\frac{gm\ \ in}{den\ \ in} \times 100\right)$
Nylon, Du Pont 300	Avg	109.1	9.24	13.2	64.6
420-68-1Z	CV	6.4	2.5	4.0	
Nylon, Du Pont 330	Avg	94.2	7.94	14.7	70.7
70-34-Z	CV	2.7	2.3	1.5	
Nylon, Du Pont 702	Avg	117.4	9.60	16.4	76.6
840-140-1/2Z	CV	3.3	1.1	3.6	
Nylon, Du Pont 728	Avg	108.2	10.24	16.3	73.0
840-140-R20	CV	2.4	1.4	4.2	
Nylon, Monsanto A07	Avg	134.7	10.90	14.6	61.3
840-140-1/3Z	CV	5.6	2.0	3.2	
Polypropylene, Hercules 301	Avg	41.5	7.84	25.8	109.9
840-140-0	CV	2.9	1.5	1.6	
Polypropylene, ICI U100	Avg	89.1	8.65	16.8	91.6
1140-228	CV	3.1	3.3	8.2	
Polypropylene, NLABS Experimental	Avg	43.5	7.05	21.2	88.9
VEE-1604/S	CV	2.0	2.6	6.1	
Fortisan 36, Celanese	Avg	208.0	9.54	6.6	33.9
800-800	CV	7.6	3.6	---[a]	
Nomex, Du Pont 430	Avg	120.1	5.54	21.2	95.3
200-100-0	CV	6.0	1.9	6.3	
Polyester, Fiber Ind 770	Avg	116.0	8.54	9.8	39.1
440-96-1/4Z	CV	4.7	2.3	3.0	

[a]Not applicable, see text.

TABLE III

PERCENT CHANGES IN YARN TENSILE PROPERTIES

Yarn		Modulus	Maximum Tenaicty	Rupture Elongation	Energy
Nylon, Du Pont 330 420-68-1Z	%	+19.6	+19.1	-24.1	-13.8
Nylon, Du Pont 300 70-34-Z	%	+26.4	+14.8	-21.8	-15.5
Nylon, Du Pont 702 840-140-1/2Z	%	+36.2	+13.7	-14.6	-14.6
Nylon, Du Pont 728 840-140-R20	%	+29.1	+10.7	-16.3	-12.5
Nylon, Monsanto A07 840-140-1/3Z	%	+20.2	+ 9.0	- 9.9	-15.1
Polypropylene, Hercules 301 840-140-0	%	-24.1	+27.9	-21.8	-23.7
Polypropylene, ICI U100 1140-228	%	- 1.5	+14.6	-12.0	0
Polypropylene, NLABS Experimental VEE-1604/S	%	+31.4	+ 2.3	-38.0	-40.7
Fortisan 36, Celanese 800-800	%	+ 6.1	+14.8	- 4.3	+12.9
Nomex, Du Pont 430 200-100-0	%	- 0.7	+ 5.1	- 3.6	+ 6.6
Polyester, Fiber Ind 770 440-96-1/4Z	%	+ 4.5	+ 9.5	- 18.3	- 23.8

The purpose of the Instron and piston tests was to provide a basis on which yarns could be selected for later use in model structures. Twenty-seven yarns were Instron tested; then eleven of the original twenty-seven yarns were selected for piston testing. Based on the piston data in Table II, fewer than eleven yarns were chosen for ballistic evaluation.

The materials in Table II may be divided into the following groups: five nylons, three polypropylenes, and one each of polyester, Nomex and Fortisan. The polyester properties are not attractive, so that yarn was dropped. Based on its high temperature properties Nomex was kept. That left the nylon and polypropylene groups. To aid discussion of the remaining yarns, Table IV was constructed.

TABLE IV

COMPARISON OF YARNS
(Piston Data - Highest Values)

	Modulus	Tenacity	Elongation	Energy
Overall	Fortisan	A07 nylon	301 polyprop	301 polyprop
Nylon	A07	A07	702	702
Polyprop	U100	U100	301	301

The four criteria shown are modulus, tenacity, elongation and energy. The materials listed have the highest values of the respective properties. The NLABS polypropylene VEE-1604/S is not superior to the U100 or 301 in any respect and was dropped. Of the remaining materials, the attractive properties are distributed among many yarns. Thus the U100 and 301 polypropylenes were tested as well as the 702 and A07 nylons. Referring to Table II, the 728 nylon appears to possess a balance of properties which may lead to good ballistic performance. The 728 was kept for testing. Also the 330 was kept for later studies of the effect of denier per filament variations on felt ballistic performance.

Based on the preceding discussion, the following nine yarns were selected for critical velocity measurements.

1) Du Pont nylon type 330, 420-68-1Z
2) Du Pont nylon type 330, 70-34-Z
3) Du Pont nylon type 702, 840-140-1/2Z
4) Du Pont nylon type 728, 840-140-R20
5) Monsanto nylon type A07, 840-140-1/3Z
6) ICI polypropylene type 301, 840-140-0
7) Hercules polypropylene type 301, 840-140-0
8) Du Pont Nomex type 430, 200-100-0
9) Celanese Fortisan 36, 800-800.

4. LONGITUDINAL WAVE SPEED AS A FUNCTION OF STRAIN LEVEL

The high speed piston test described in the preceding section is one method for obtaining information regarding the dynamic properties of yarns. Another is the determination of the speed of propagation of longitudinal elastic waves in yarns. In this section the experimental technique for measuring the wave velocity as a function of strain is described and the results presented.

a. Description of Experimental Technique

The velocity of propagation of longitudinal strain waves was measured as a function of strain by simultaneously using the Instron and the Pulse Propagation Meter (H. M. Morgan & Co., Cambridge, Mass.). The latter instrument measures the time for discrete strain pulses to travel along the yarn length by means of two piezoelectric ceramic transducers to which are bonded metal tabs with notched ends for contacting the yarn. The transducers have a natural frequency of 5 kilocycles per second and are pulsed at 60 cps. The time for the sonic pulses to travel along the yarn from one transducer to the other is measured.

The strain wave velocity is obtained as a function of yarn strain by performing the test with the sample mounted in an Instron. One of the crystals is fixed to the Instron frame and the other to the crosshead. Both the propagation time and specimen strain are recorded as a function of time. A delay time must be subtracted from the recorded times in order to obtain the true propagation time. This delay time represents the time it would take a pulse to travel from one crystal to the other if the crystals were immediately adjacent to each other. It is determined by tensioning the yarn specimen by a dead weight loading, keeping one crystal stationary and recording the propagation time as a function of the distance between the crystals as the other crystal moves along the yarn length. The delay time is then the time given by extrapolating this recorded line to zero crystal separation.

b. Summary of Results

Using the technique described above, velocity-strain measurements were made on the same eleven yarns that were piston tested. The results are summarized in Figures 11 12, and 13. The yarns were conditioned and tested at 65%RH and 70°F. The maximum strain imposed in these measurements is approximately 75% of the yarn rupture strain; the yarns were not ruptured to avoid possible damage to the delicate transducers.

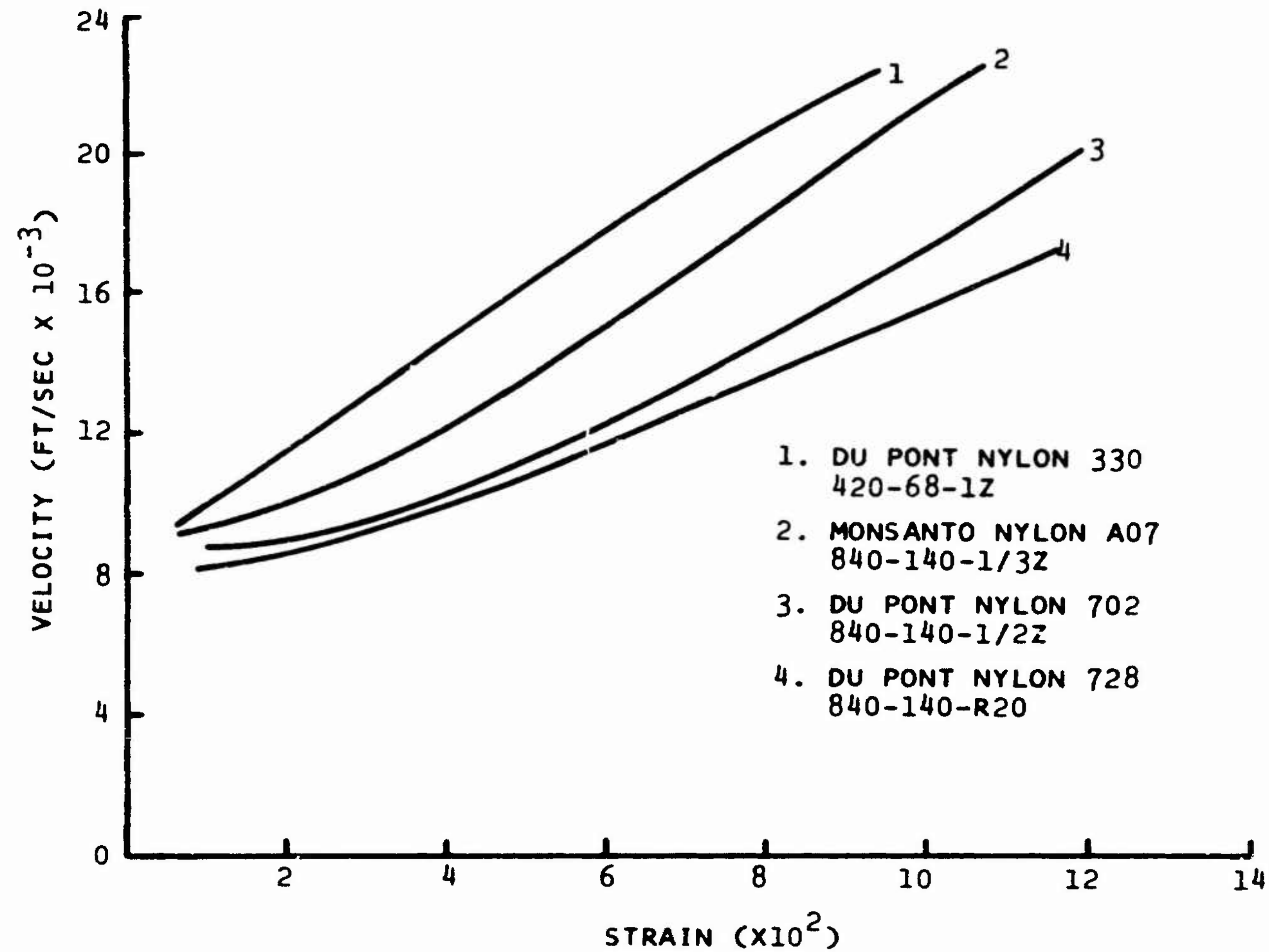


Figure 11. Wave Velocity vs Strain - Nylons

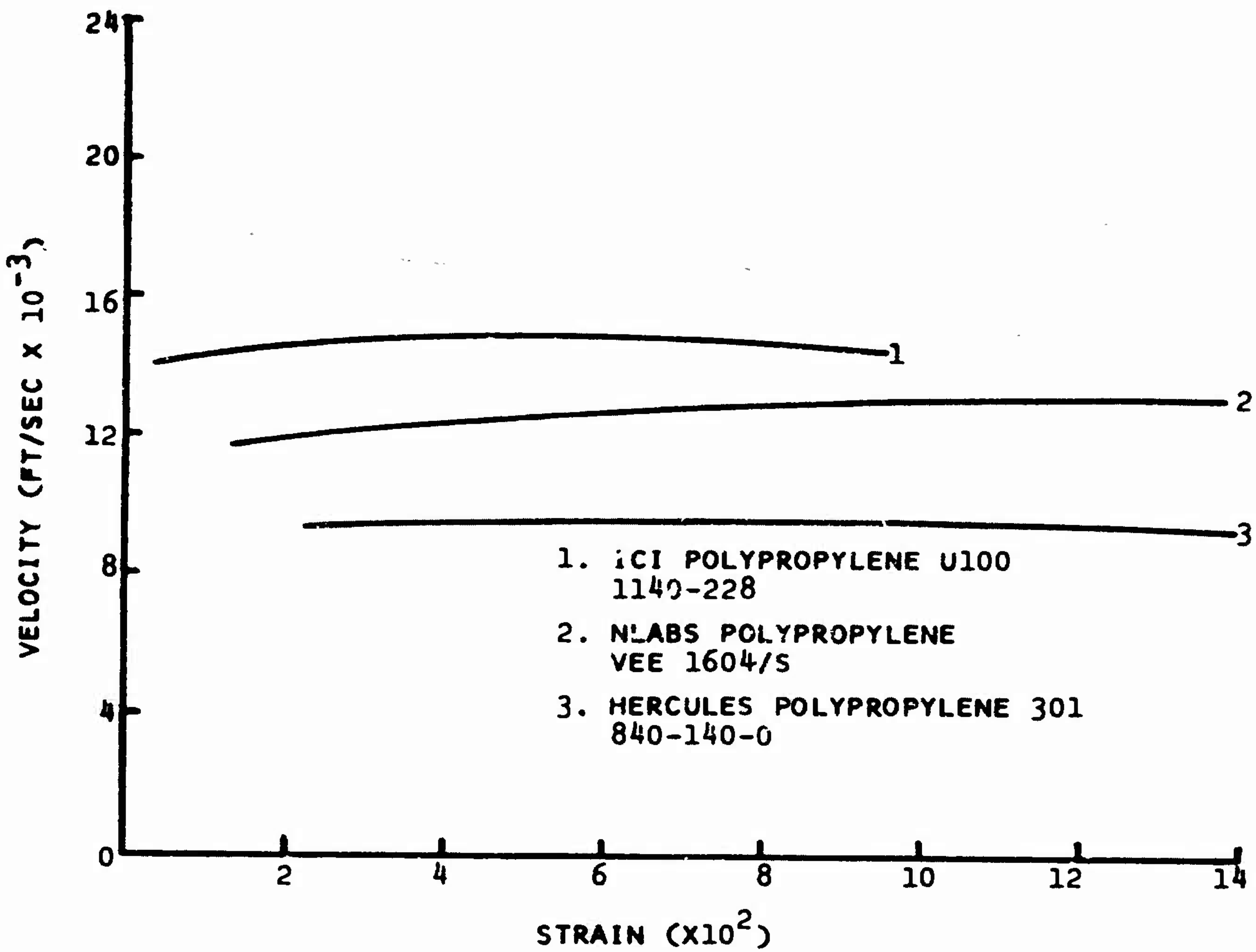


Figure 12. Wave Velocity vs Strain - Polypropylenes

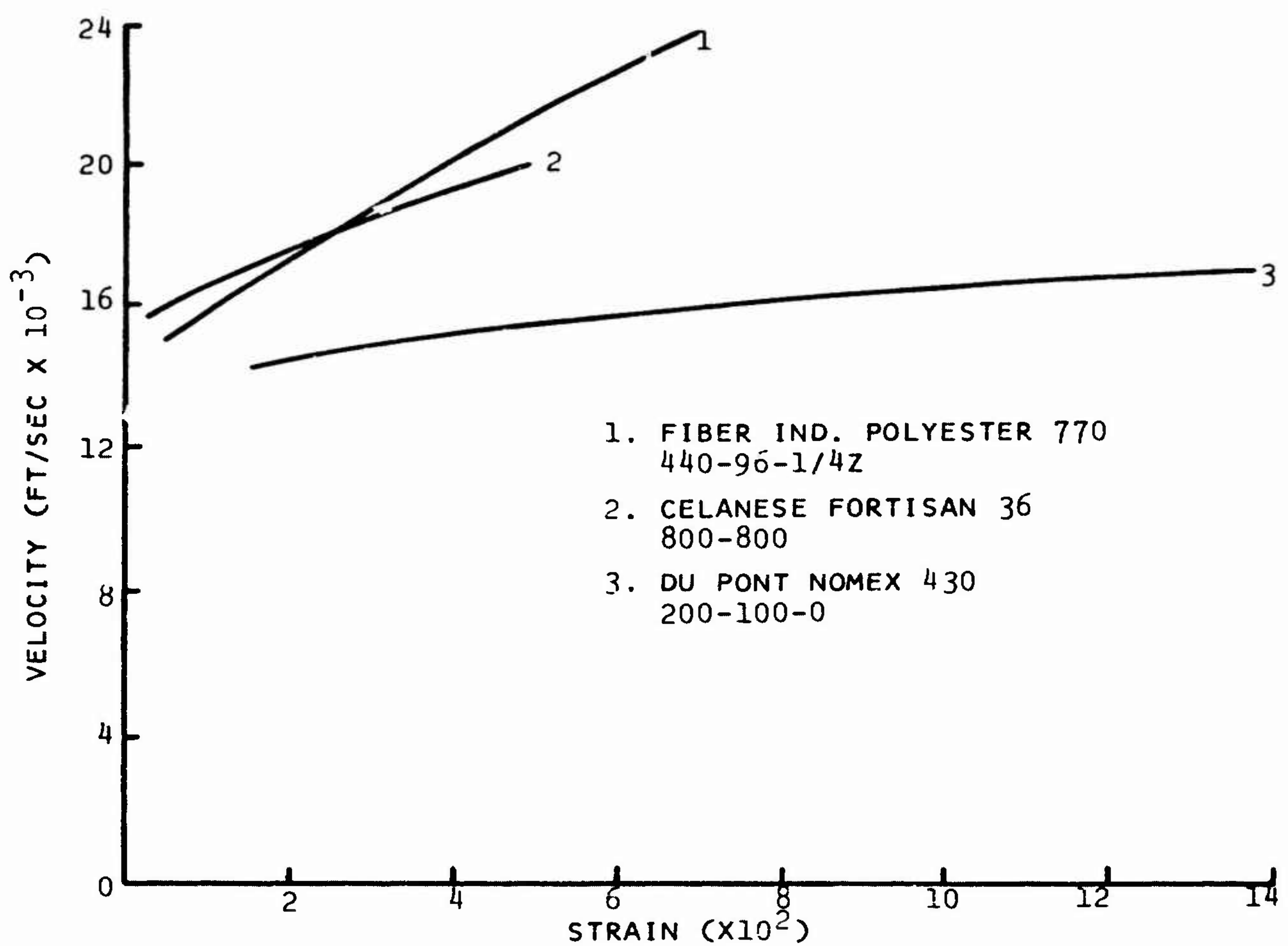


Figure 13. Wave Velocity vs Strain - Polyester, Fortisan and Nomex

Notice that there are only ten curves for the eleven yarns in Figures 11-13. This is because the eleventh curve would be for the Du Pont nylon type 330, 70 denier yarn. That curve is identical to the type 330 of 420 denier yarn. The wave velocity in the yarn is not affected by linear density, but depends on volume density (see below) which is the same for both the 420 and the 70 denier type 330 yarns.

Figures 11-13 show that in general the wave speed increases with increasing strain level. An attempt was made to utilize this phenomenon to enhance ballistic performance by introducing some prestraining in model textile systems. The impacting missile energy is partly dissipated by waves traveling away from the point of impact. By prestraining the constituent yarns, waves in the structure will propagate faster than in the corresponding unstrained structure and thus more material will absorb energy in a given time interval.

c. Discussion

Consideration of the combined PPM-Instron apparatus leads to the following analysis of the test results. The Instron is used to apply to the yarn an initial strain and then the PPM initiates a small superposed dynamic strain pulse at one end of the yarn. The strain wave travels down the yarn and is picked up at the other end by a piezoelectric transducer. During the wave's passage down the yarn, the initial stress state may be considered static because the Instron crosshead motion is negligible during a time interval on the order of the wave transit time. Thus a small, elastic strain pulse is being dynamically propagated down a material under a static state of initial stress.

Figures 11-13 show that the wave velocity increases markedly with increasing strain except for the polypropylenes. It has been found experimentally that for elastic-perfectly-plastic materials, if the material is strained into the plastic region, a PPM pulse travels with the elastic wave velocity. Thus for the nonlinear yarns the strain wave is expected to travel with at least the elastic wave speed. Second, during straining the polymer is undergoing molecular reorientation, so the strained yarn is molecularly different from the initial yarn.

Considering for a moment the initial yarn, one would expect to be able to predict the pulse velocity c at zero strain from

$$c = (0.95E)^{1/2} \times 10^3 \qquad (1)$$

where c is in ft/sec and E is the piston modulus in gm/den.

Equation (1) is the familiar $(E/\rho)^{1/2}$ in textile units. Results of evaluating Equation (1) are shown in Table V. Comparison of the calculated pulse velocities in Table V with the extrapolated measured velocities at zero strain in Figures 11-13 shows fair agreement.

TABLE V

STRAIN WAVE VELOCITIES

Yarn	Piston Modulus (gpd)	Calculated Pulse Velocity (x 10^3 fps)	Measured (extrapolated) Pulse Velocity (x 10^3 fps)
Nylon			
Du Pont 330 (420 den)	109.1	10.2	8.5
Du Pont 702	117.4	10.5	9.0
Du Pont 728	108.2	10.1	8.0
Monsanto A07	134.7	11.3	9.5
Polypropylene			
ICI U100	89.1	9.20	14.0
Hercules 301	41.5	6.28	9.0
NLABS VEE-1604/S	43.5	6.43	11.0
Polyester			
Fiber Ind 770	116.0	10.5	14.5
Fortisan	20[illegible].0	14.0	15.5
Nomex	120.0	10.8	13.5

The significant velocity changes with tensile strain are believed to be due to some kind of molecular reorientation in the fibers.(7,8) Hence the fiber birefringence would be expected to reflect this process by also changing significantly. Preliminary measurements showed that the fiber birefringence remained virtually constant over a 0-15% elongation range. This unexpected result is rationalized by considering the yarn manufacturing process. Apparently the yarns were drawn to an extent that further elongation caused no additional birefringence change.(9) In conclusion, the cursory birefringence measurements were of no help in obtaining information about the molecular reorientation that is probably taking place.

5. TRANSVERSE CRITICAL VELOCITY

Candidate yarns were screened ballistically by measuring their transverse critical velocities. Depending on the missile impact velocity, a single yarn will either bow out

following the missile or fail rather suddenly, the first deformation being energy absorbing and of interest from an armor point of view. The characteristic velocity marking the boundary between these two deformation patterns is called the transverse critical velocity. Past experience has shown that the transverse critical velocity is a useful parameter for ranking the ballistic performance of yarns. The critical velocities for the nine candidate materials were measured and are reported herein. Discussions of the test procedure and an example test precede the presentation of the data.

a. Preliminaries

The concept of transverse critical velocity of a single yarn rests on physical observations of the dynamic response of yarn to ballistic impact as illustrated in Figure 16. These photographs are multiple exposures of three yarns impacted with a notched dart. Two distinct deformation patterns are evident: at low impact velocity, the yarn is greatly deflected into a "tent" configuration, and at high impact velocity, the yarn fails so soon after impact that there is no evidence of any tenting (the transverse deflection resembles a "clamshell" configuration). These two deformation patterns are separated, imprecisely, by a "critical" velocity designated the transverse critical velocity (TCV). The actual experimental technique used to measure the TCV is discussed in the next section.

The emphasis which is being placed on the yarn deformation patterns is new to this field. Previous investigations[2,10,11] defined TCV as the lowest missile impact velocity which caused yarn failure within a pre-selected number of microseconds after impact, varying from 10 to 50. (In Figure 14 the multiple exposures are at 20 microsecond intervals.) Use of that failure criterion requires a skilled ballistician experienced in interpreting high speed photographs of yarn impact. Since critical velocity is not a definite measurement like reading a dial on an instrument, results from different sources are subject to variation.

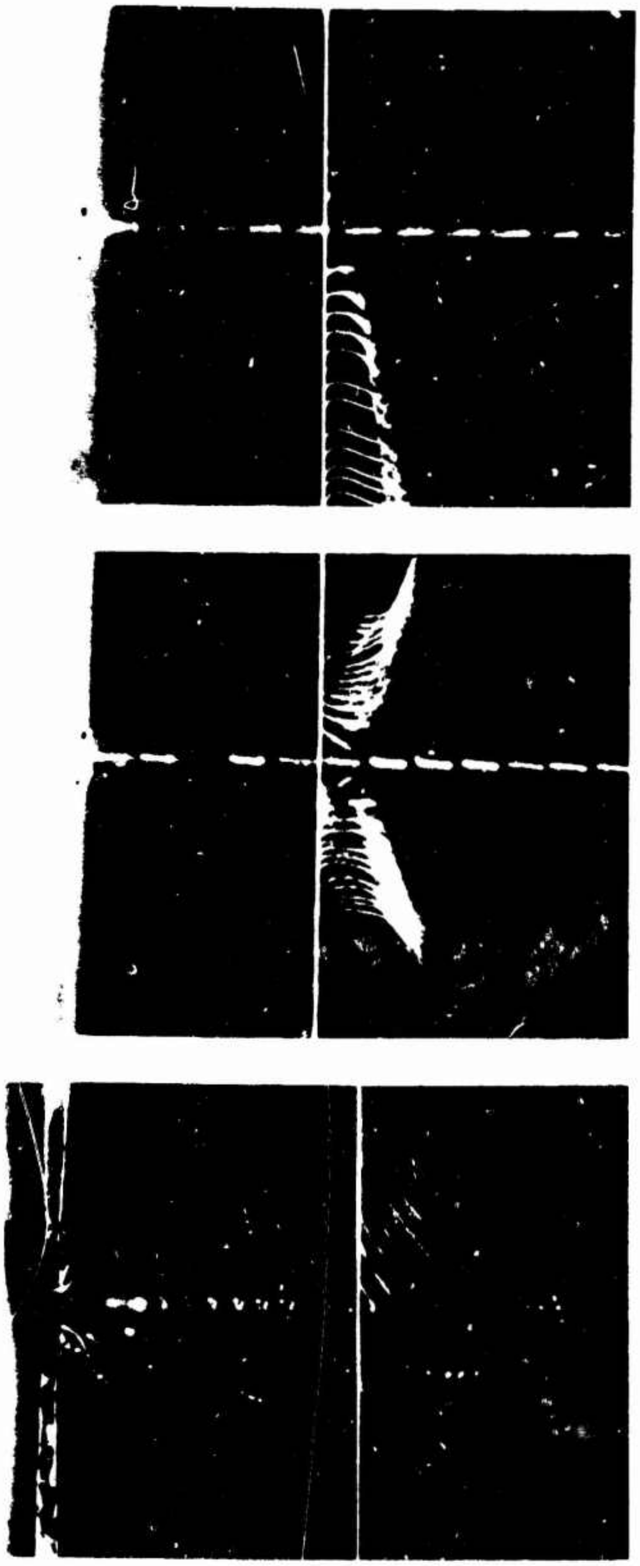
Based on past experience with a 50 microsecond failure criterion, it was initially believed that using a 20 microsecond criterion would lead to a more accurate determination of critical velocity. A 20 microsecond interval was tried but it did not produce the expected improvement. Series of photographs were obtained showing the same deformation patterns and all showing apparent yarn failure very near 20 microseconds after impact, but the impact velocity varied over a 500 ft/sec range. Thus choosing the unique transverse critical velocity by the 20 microsecond criterion proved to be practically impossible.

The next step was to re-examine the purpose of the transverse critical velocity measurement. The TCV is intended to provide information about the potential ballistic performance of a yarn; if for all impact velocities the yarn "fails immediately" common sense dictates that the material would probably be useless armor. Along this line, the important distinction would seem to be the difference in deformation patterns of the yarn impacted at different velocities. At low velocities the yarn "tents out" while at high velocities it fails immediately. Presumably the tenting action is relevant to energy absorption in an armor material, and rapid yarn failure would be indicative of rapid armor failure. The velocity at which this change in deformation patterns occurs is more reliably selected than the velocity at which yarn failure occurs within a fixed number of microseconds. The difference in deformation patterns is clearly illustrated in Figure 14 by the lower two photographs.

The new transverse critical velocity procedure described above is intended to emphasize the physical fact that at low impact velocities a yarn responds in one deformation mode and at high impact velocities another mode. The relation between this procedure and the other definitions mentioned above is closer than may be expected. The 40-50 microsecond definition gives values about 100 ft/sec higher than our new procedure. Our unsuccessful attempts with a 20 microsecond definition indicate that using a smaller time interval does not lead to "more accurate" determinations of transverse critical velocity.

b. Experimental Procedure

Three main components are required to measure transverse critical velocity: a rifle, a high-speed photographic system, and a bullet velocity measuring system. Essentially a vertically suspended yarn is struck transversely by a notched missile which engages and breaks the yarn. A sketch of TCV equipment layout is shown in Figure 15. A yarn is suspended vertically in a sample mount which looks like free-standing Instron jaws. A smooth bore .22 caliber Hornet rifle (Winchester Model 43-22 with hand loaded Hornet Super X center fired cartridges) is used to fire a hardened and polished steel notched dart to engage the yarn. After the yarn is broken, the missile penetrates two electrically conducting grid papers which actuate a solid-state timer (Southwest Technical Products, San Antonio, Texas). The missile is then caught in layers of woven ballistic nylon placed inside an armor steel bullet trap. The missile is undamaged by the nylon panel and is reused. The time reads directly in microseconds. The missile velocity is computed by dividing the distance between the grid papers by the timer reading.



Above transverse critical velocity

Near transverse critical velocity

Below transverse critical velocity

Figure 14. Ballistic Impact of a Yarn

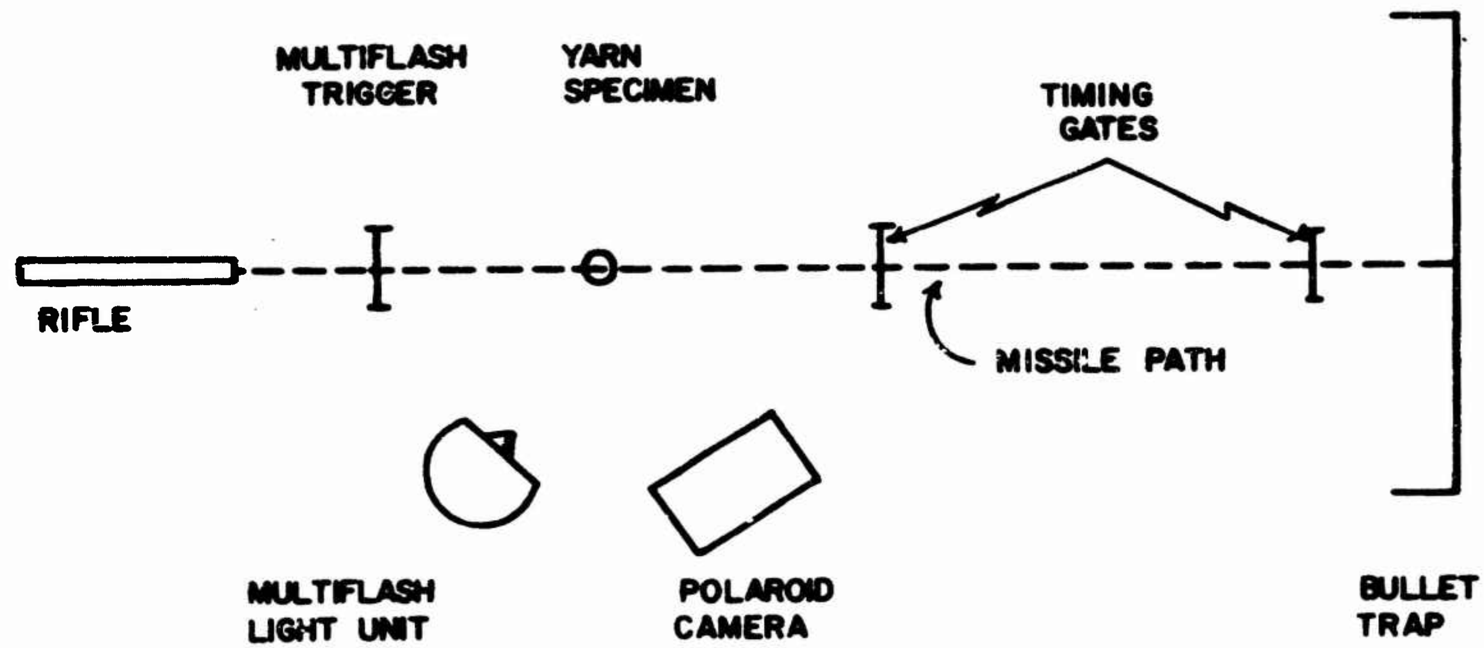


Figure 15. Transverse Critical Velocity Layout - Top View

Multiple exposure Polaroid pictures are taken of the impact event. After leaving the rifle barrel, the missile cuts an aluminum foil strip, triggering a flashing light (EG&G Multiple Microflash Unit LS-10) which illuminates the impacted yarn. The flashing rate of the multiflash can be adjusted within the range of 1,000-100,000 flashes per second. Fifty thousand flashes per second were used so that the multiple exposures of the impacted yarn appear on the Polaroid film at 20 microsecond intervals.

A test is run by hand loading a gun powder charge into a cartridge, firing the notched dart at the yarn, and recording the impact event on Polaroid film. At the start, depending upon the velocity of the missile and the type of yarn, the first impact test may be above, near, or below the transverse critical velocity of the yarn. Three pictures are shown in Figure 14 of typical responses of yarns. The pictures are multiple exposures of the same yarn.

To determine the transverse critical velocity of a yarn, a sample is selected and impacted by the procedure described above. The picture is examined, and, depending upon the yarn deformation observed, the powder charge is changed. Additional shots are made with the powder charge being incrementally changed until a sequence of photographs is taken. By examining an entire sequence of photographs of the yarn being impacted at different velocities, the transverse critical velocity can be selected.

The velocity at which the change in deformation pattern from a tent configuration to an open clamshell occurs was designated the transverse critical velocity. The velocity is "critical" in the sense that it marks the change in deformation phenomena. By this procedure, two pictures are selected showing the two deformation patterns, and the TCV is taken as the average of those two impact velocities. The pictures usually allow bracketing the TCV based on this technique with 100 fps. For example, with a definite clamshell picture at 1650 fps and a definite tent at 1450 fps, the TCV would be designated as 1550 fps and would be bracketed with 100 fps. This procedure was followed in obtaining the transverse critical velocities reported in the next section.

To obtain sufficiently clear photographs, a fraction of a turn per inch of twist was inserted in the yarn prior to mounting the specimen. Past experience has shown that such low twist has no effect on critical velocity; however it should be noted that several photographs indicate that this point could be questioned and might be profitably investigated thoroughly at a future date.

c. Example Critical Velocity Shots for One Material

Between 10 and 25 shots were necessary for each yarn in order to generate a usable sequence of TCV photographs. It is impractical to reproduce the photographic sequence here, but one sequence of impact velocities and descriptive comments is presented to illustrate the amount of firing required to determine the TCV for one material, Du Pont nylon type 728, 840-140-R20. The flashes were at 20 microsecond intervals so that the deformation patterns described under "Comments" below correlate with Figure 14. Thus "no failure after 8 tents" means tenting deformation for at least 160 microseconds after impact with no failure.

FRL® Shot Number	Velocity (fps)	Comments
205	1720	8 tents. No failure.
207	1730	3 tents. Failed in fourth.
206	1790	1 tent. Failed in second. Little clamshell.
203	1825	1 tent. Failed in second. Little clamshell.
202	1840	1 tent. Failed in second. More open clamshell.
209	1890	1 tent. Failed in second. More open clamshell.
198	2010	First tent failed. Open clamshell.
199	2040	First tent failed. Open clamshell.
197	2170	First tent failed. Open clamshell.

Pictures of Nos. 207 and 209 were selected as bracketing the velocity at which the deformation patterns changed; the average velocity of the two pictures is 1810 fps, designated the transverse critical velocity. In this example, the TCV is bracketed by 80 fps.

d. Test Results and Discussion

Using the experimental procedure described above, the transverse critical velocities of the nine candidate yarns were determined. The results are tabulated in Table VI. The TCV's are approximately distributed over a 500 fps range.

TABLE VI

TRANSVERSE CRITICAL VELOCITIES

	(fps)
Du Pont nylon type 702, 840-140-1/2Z	2000
Monsanto nylon type A07, 840-140-1/3Z	1880
Du Pont nylon type 728, 840-140-R20	1810
Du Pont nylon type 300, 420 68-1Z	1785
ICI polypropylene type U100, 1140-228	1730
Hercules polypropylene type 301, 840-140-0	1700
Du Pont Nomex type 430, 200-100-0	1475
Du Pont nylon type 330, 70-34-Z	1475

In addition, the effect of tension (dead weight loading) on transverse critical velocity was investigated using three materials. Tension enables the longitudinal wave to propagate away from the point of impact faster than in the untensioned specimen, while at the same time the pretension uses part of the available elongation in the material; it was not known how these two competing factors influenced the critical velocity. For all three materials, tension reduced the critical velocity, the reduction being most dramatic for the 702 nylon. These data are reported in Table VII. The pretension was approximately 60% of the static rupture load.

TABLE VII

CRITICAL VELOCITIES OF TENSIONED YARNS

	(fps)
ICI polypropylene	1500
Du Pont nylon type 702	1200
Nomex	1100

The nine candidate materials possess transverse critical velocities ranging approximately from 1500 to 2000 ft/sec. The materials are spread fairly evenly over that interval with no distinguishable grouping apparent. The highest tenacity nylons generally have the highest critical velocities. There appears to be no direct correlation between any of the previously measured high strain rate properties and critical velocity. For comparison with the critical velocity ranking in Table VI, the same materials are ranked in Table VIII according to the high strain rate properties above. The materials are listed in decreasing order of property, e.g., the highest modulus material is at the top of the table.

TABLE VIII

HIGH STRAIN RATE RANKING OF YARNS

Modulus	Tenacity	Elongation	Energy
Fortisan	A07	301	301
A07	728	Nomex	Nomex
Nomex	702	U100	U100
702	Fortisan	702	702
330	330	728	728
(420 den)	(420 den)	330	330
728	U100	(70 den)	(70 den)
330	330	A07	330
(70 den)	(70 den)	330	(420 den)
U100	301	(420 den)	A07
301	Nomex	Fortisan	Fortisan

e. Error Analysis

Determining the missile velocity required, of course, the measurement of two quantities - the distance the missile travels and the elapsed time for covering that distance. The velocity V is then computed by dividing the distance between the timing screens X by time T; $V = X/T$. These two measurements contain errors which then cause an error in the computed velocity. The fractional errors in X and T, $\Delta X/X$ and $\Delta T/T$, add to give an estimate of the maximum expected fractional error in velocity.

$$\frac{\Delta V}{V} = \frac{\Delta X}{X} + \frac{\Delta T}{T}$$

The velocity error can also be written as

$$\frac{\Delta V}{V} = (\Delta X + V\Delta T)\frac{1}{X}$$

which shows that the fractional velocity error increases linearly with V and decreases as 1/X.

The V_{50} specification (MIL-STD-662A) requires that the grid distance be maintained to within 0.125 inch; so $\Delta X = 0.125/12$ ft. Our chronograph error is $\Delta T \doteq 10$ μsec = 10×10^{-6} sec. Using these values for ΔX and ΔT and defining the percent error in velocity and $100\ \Delta V/V$, Figures 16 and 17 were constructed. Under the conditions we are using, the velocity error is not expected to exceed 1%.

Small variations in operating procedure which affect missile velocity seem to have been minimized; amount of spent cartridge resizing, placement of the notched dart in the cartridge, and other factors presumably have some effect on missile velocity. However, firing several shots using the same powder charge each time resulted in quite reproducible missile velocities as shown below. Checks were made near 1000 ft/sec and 2000 ft/sec.

Shot No.	Powder Charge (grains)		Velocity (ft/sec)
221	2.00		1150
222	2.00		1132
223	2.00		1138
224	2.00		1123
225	2.00		1140
		Average =	1137
99	4.30		2010
100	4.30		2110
101	4.30		2070
102	4.30		2030
103	4.30		2040
		Average =	2052

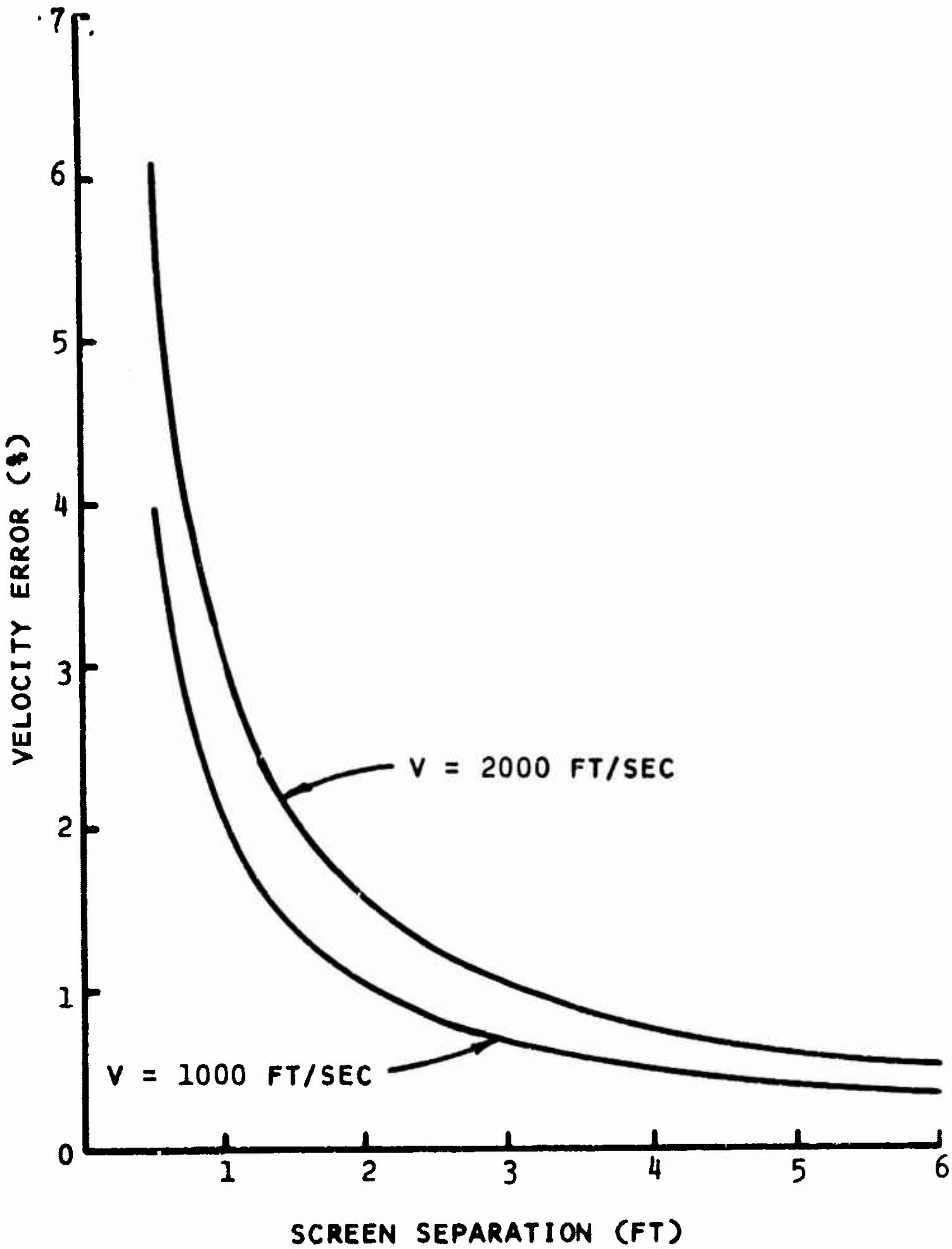


Figure 16. Velocity Error vs Screen Separation

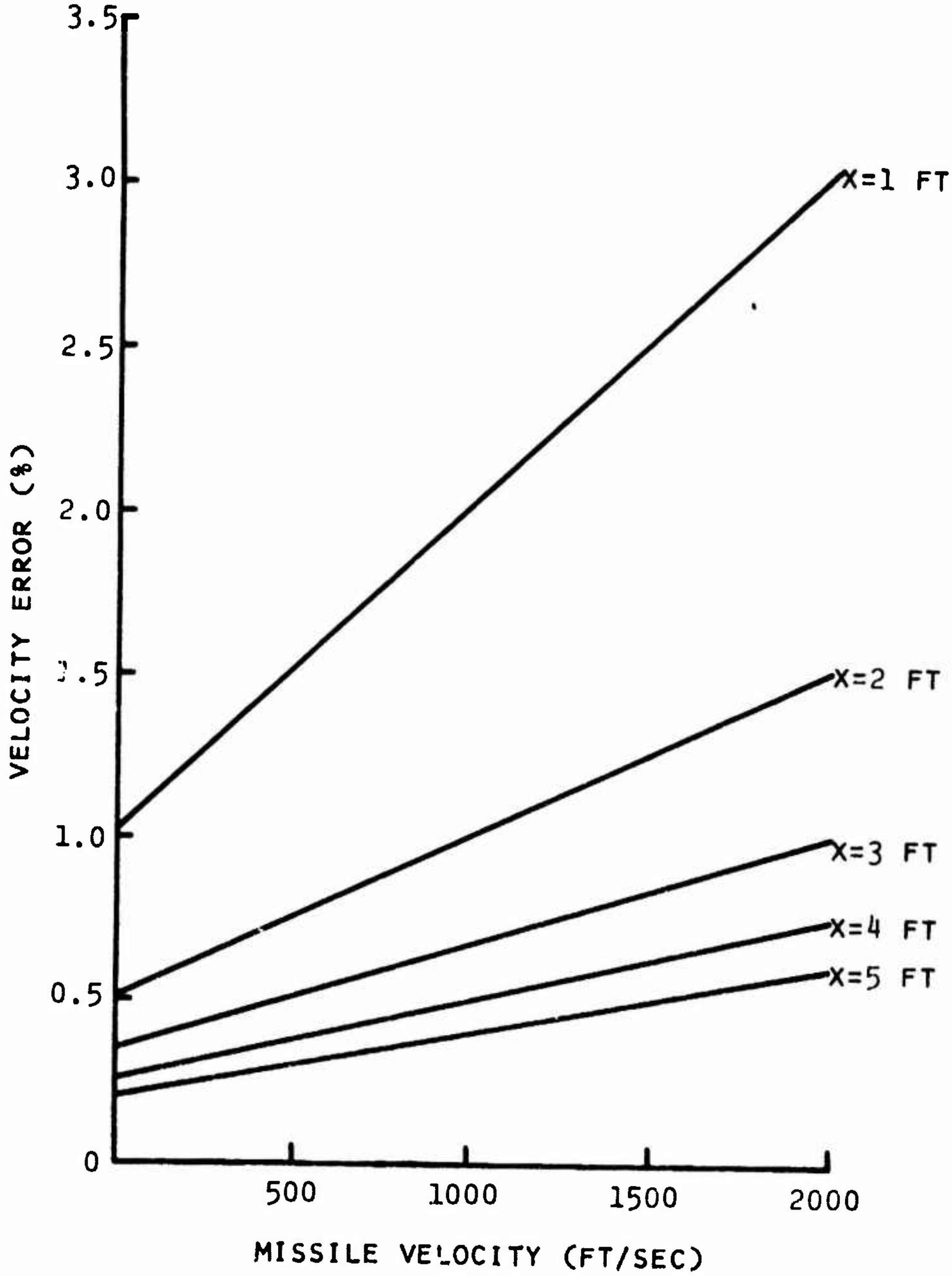


Figure 17. Velocity Error vs Missile Velocity

Another possible source of error in missile velocity is aerodynamic drag. MIL-STD-662A contains an air drag coefficient K_D for the V_{50} fragment simulator for use in the V_{50} test. The drag coefficient for a body moving through a fluid depends on the shape of the moving body; therefore the V_{50} drag coefficient is not directly applicable to the FRL® notched dart. However, to get an idea of the magnitude of the velocity correction probably applicable to the notched dart, two calculations were carried out as outlined in MIL-STD-662A. At the 1000 ft/sec level, the V_{50} missile loses 21 ft/sec in traveling the five feet between the velocity measuring station and the target, and at 2000 ft/sec it loses 55 ft/sec. The "velocity measuring station" is defined as the midpoint between the timing grids. With regard to yarn critical velocities, it is noted that the distance between the impacted yarn and the velocity measuring station is less than five feet so the velocity loss would be less than that indicated above if the two missile drag coefficients were the same. Since the drag coefficient of the notched dart is not known (it is probably less than the V_{50} drag coefficient) an air drag correction was not applied to transverse critical velocity data. An estimate would be that the reported critical velocities are 25 ft/sec low because of air drag.

6. CONCLUSIONS AND DISCUSSION

The observed differences between low and high strain rate behavior of polymeric yarns illustrate the care which must be taken in selecting materials for high strain rate applications. In general, the modulus and strength increases and the elongation-to-break decreases with increasing strain rate. Thus, if a particular property is required for achieving a desired performance level, the appropriate strain rate must be considered. Monsanto nylon type A07 and Du Pont nylon type 728 exhibited the highest tenacities at high strain rate of the yarns evaluated on the program; their tenacities were 10.9 gpd and 10.2 gpd respectively.

The elastic pulse propagation speed in nylon yarn was found to increase nearly three-fold with increasing strain level. No such increase was observed in polypropylene. The exact relationship between this effect and basic polymer structure is unknown in spite of the extensive programs and recent results in the area of polymer morphology.

The only ballistic screening test used yielded the result that Du Pont nylon type 702 exhibited the highest transverse critical velocity of 2000 fps.

The techniques which were used on this program have wide applicability beyond ballistics to include such high strain rate applications as air bags, automobile seat belts, and parachutes. The exact application requires a trade-off in material properties, and the techniques described in this report can be used to characterize the mechanical properties of textile materials over a broad range of strain rates.

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